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Assessing Suppliers for Complex Products from the Perspective of Power

Yan Liu, Claudia M. Eckert, and Chris Earl

Abstract—Innovation steps in complex products often go hand in hand with the selection of suppliers. The suppliers are involved in the development of innovative elements of products, supplementing the capabilities of companies. Strategic relationships are established with these suppliers, where the companies need them to be flexible and willing to adapt to changing demands. Flexibility is usually evaluated against a variety of indicators. However, a high score on flexibility does not guarantee cooperative suppliers. Companies also require power to get a supplier to be flexible. They need suppliers who are malleable to their changing needs that are an inevitable part of design processes. The empirical study at a leading European engine company reported in this paper shows that the relative power between companies and suppliers influences the responsiveness of suppliers to requests. This paper analyses malleability as a combination of flexibility and relative power. It unpacks power and flexibility into sets of measurable indicators and proposes a tool which assesses both the relative power between buyer and supplier and the supplier's flexibility, to provide a malleability index, which indicates to what extent a supplier is suitable to work with.

Index Terms— Decision making, malleability index, flexibility, power, product innovation and development, TOPSIS

Managerial Relevance Statement—Companies require suppliers who are able and willing to respond to the changing needs of companies during the innovation processes. This is not only a matter of the flexibility of suppliers, but also of the relative power of companies to make suppliers flexible. The malleability index proposed in this paper offers managers a convenient way to assure that the selected suppliers are not only technically competent and cost effective, but also willing to be flexible in a way to suit the needs of the companies to enable innovation. This paper also contributes a decision tool for industry, which assesses the malleability of suppliers. It follows a simple logic to weight up different indicators and compare the indicators against a best and a worst case scenarios. The tool also helps different decision makers to reach a consensus about the weights of the indicator and the performance of the suppliers against each indicator, thereby it allows the decision makers to reflect over their priorities.

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I. INTRODUCTION

Innovation and development of complex products take place under uncertainty. The technology and its future development is complicated and unpredictable [1, 2], the cost of using suppliers fluctuates [3], and the company's requirements and demands change [4]. Complex products have many standard parts, for which companies usually have long-term suppliers, but other elements are new and innovative, for which they need to find collaborative suppliers to reduce uncertainty and associated risk [5, 6]. These suppliers might get involved in the development process, supplementing the capabilities of companies by providing not only parts but also knowledge, technology, innovative ideas, and design solutions; or they need to respond to enquiries and changing demands of companies. Therefore, companies look for suppliers that are capable to meet their requests, but also whom they can influence to adapt to changes in the product, the means of production or the required time scale or volume. A company wants suppliers who are malleable, i.e. capable and willing to accommodate changing demands and requirements. This paper argues for the importance of assessing power in conjunction with flexibility in supplier selection to assure that suppliers are not only technically competent and cost effective, but also of high likelihood to be flexible to suit the needs of a company to enable innovation. The paper combines the assessments of power and flexibility into a malleability index for supplier assessment and proposes a tool to calculate this index.

The paper draws on a case in a company that designs and produces off-highway diesel engines. The company is a first-tier supplier to many different original equipment manufacturers (OEMs), while also producing generator sets that they sell directly to the end customers. They have a complex supply chain themselves in which they often compete for suppliers with car companies, who have much larger volumes. They therefore have exposure to power issues both as a customer and as a supplier. As diesel engines are a mature technology and many components are carried through between product generations, they have many well-established suppliers. However, they also must look for new suppliers as more and more sensors and electronic technology are integrated in the engine. A company needs new suppliers if the product changes in ways that the existing suppliers cannot accommodate or it enters new markets the suppliers cannot serve. To

be competitive they need competent and responsive suppliers to enable them to respond to their customer's changing needs.

Malleability means that a supplier is able and likely to be flexible. For example, companies define their design solutions but need to make late changes to detailed geometry, or they need to change the order volume from that indicated in the call for tender. A supplier able to accommodate these changes is considered flexible. However, a flexible supplier might not choose to deliver on its flexibility. This depends on how the supplier perceives the relation. If the supplier has needs from the buyer, for example for profit or knowledge, it would accommodate the buyer. In this case the supplier depends on the buyer, which gives the buyer power according to the resource-dependence theory [7] and power-dependence theory [8]. Power is relational involving mutual dependence, i.e. the supplier needs the buyer and vice versa to a certain extent. The asymmetry of dependence determines to what extent the supplier will be responsive to the buyer's requests. This paper analyzes whether a supplier is likely to be flexible from the perspective of power and proposes a malleability index for supplier assessment based on the combination of power and flexibility.

Power has been recognized by researchers as an important factor in supply chain management [9-11]. As the maximum potential ability of one party to influence others [12, 13], power resides implicitly in the other's dependence [7, 8]. A powerful supplier exposes the buyer to the risk of potential delays at supplier end, variation in quantity, poor quality of the products, and failure of communication and partnership [13, 14]. These risks occur when a supplier is not able or willing to respond to demand changes. On the other hand the buyer could use its power as a means to guarantee good flexibility from suppliers [15]. For example Toyota could create an assembly-based, demand-pull, and Just-In-Time system because it was able to control its suppliers [16]. The empirical study at a leading European engine company reported in this paper also shows that the relative power between companies and suppliers influences the responsiveness of suppliers to the changing demands and the continuation of supplier performance. Understanding who, whether the buyer or the supplier, is more powerful, helps the company to select a cooperative supplier.

Most of the literature on power analyses the effects of power on important aspects of relationships such as

trust [17, 18], commitment [19, 20], and willingness to share or adoption [21, 22]. Much less research has addressed the assessment of power. Power is to a certain extent a subjective concept that needs the judgements of the company experts. Cho and Chu [23] propose a way of calculating power according to eight suggested indicators that determine power, but do not consider the influence of subjective judgment. Cox [9] establishes a matrix-based model to identify power situations by identifying the power indicators rather than quantifying them. This model cannot deal with additional or fewer power indicators in that the indicators are fixed. Zolghadri et. al [24] propose power-based supplier selection models which rank potential suppliers by the ratio of supplier power to buyer power. They treat the performance criteria (e.g. net price, product quality and delivery reliability) as power indicators without offering an analysis of the sources of power. An effective quantitative assessment for power is missing in the (potential) buyer-supplier relationship.

Supplier assessment and selection has received considerable attention from both academia and industry. Suppliers are assessed for their competence against a number of indicators. Some indicators are about performance in terms of operation, management, and finance such as cost, and financial status; some reflect the potential flexibility of suppliers such as techniques and technology. This research extracts the indicators of flexibility from the general supplier assessment criteria and unpacks power into a comprehensive set of assessable power indicators by drawing on literature presented in section 2. Fig. 1 shows the typical supplier selection based on performance criteria through the arrow with the dotted line. The solid lines show the concept of the tool proposed in this paper, which combines flexibility and power to calculate the malleability index. The tool can also be used to assess general selection criteria [25]. The case study in section 3 shows the importance of power considerations in supplier selection and the need for a systematic way to understand power. A fuzzy decision tool is then presented in section 4 to determine the buyer/supplier power, based on which the power advantage is generated. It further calculates a malleability index for each supplier, which indicates to what extent a supplier is suitable to work with. As supplier assessment involves subjective and collective judgments, the tool supports synthesizing the opinions of multiple decision makers, taking the

imprecision into account. Section 5 shows how the tool would work in an illustrative example. Section 6 concludes the paper.

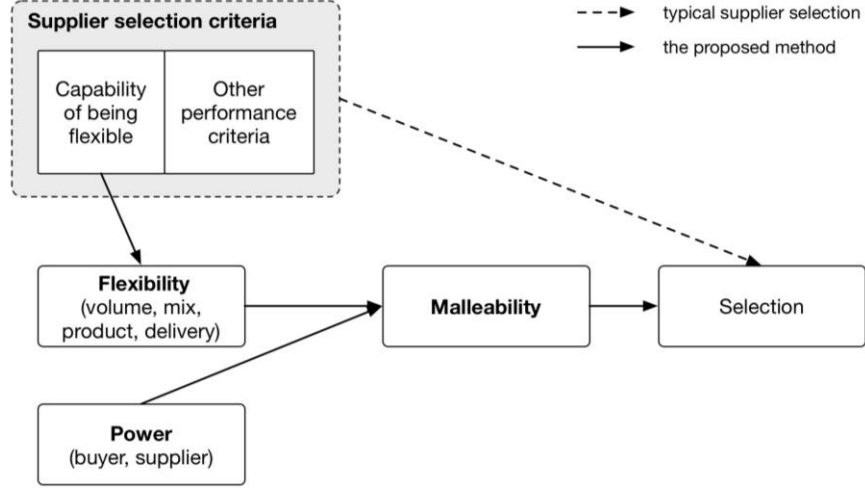


Fig. 1. The main idea of this research

II. RELATED WORK

Supplier flexibility and power advantage are the two facets of supplier malleability. A flexible supplier can adapt to the needs of buyer while a powerful buyer could ensure that it receives that flexibility. To develop an assessment model for the malleability index, this section reviews the indicators for the two facets.

A. Supplier flexibility

Uncertainty affects product innovation and development but to work with a flexible supplier helps reduce its effect. For example, technology uncertainty increases the cost for new product development [26] but by sharing information with a capable supplier, the problems associated with technology uncertainty can be mitigated [27]. Flexibility in the operational and managerial context means the ability to respond effectively to changing circumstances [28, 29]. Supplier flexibility is a multi-dimensional construct. Four major dimensions can be used to study the flexibility: volume, mix, product, and delivery flexibility [28, 30]:

-- *Volume flexibility* refers to the ability to change the aggregated production output to respond quickly and efficiently to the fluctuated demand [31, 32]. An indicator is the production capacity and facilities of the supplier because it indicates the potential of the supplier to provide the required amount of the product.

Another indicator is the reserve capacity, implying the ability of the supplier to deal with unexpected demand instantly [33].

-- **Mix flexibility** is the ability to change the range of products made within a given period [32]. This requires that the supplier has a flexible production line, which allows switching the production from one type to another rapidly. It is also characterized by short set-up time, low switching time, and high product variety [34].

-- **Product flexibility** means the ability to launch a new product, or to modify existing ones [31, 32]. It can be further distinguished as new product development flexibility and product modification flexibility [29]. Both need the suppliers to be capable in terms of techniques and technology, research and development, and dynamism of input technology to meet customization and differentiation requests. The manufacturing system is also important to product flexibility, making new parts and products using existing facilities [35].

-- **Delivery flexibility** refers to the ability to change planned or assumed delivery dates and destinations [32, 36]. Delivery reliability, the ability to meet the delivery schedules, is a key indicator [37]. The transport mode should also be considered in that fast modes allow quick delivery, granting flexible delivery schedules [38].

These four dimensions provide measurable indicators for assessing supplier flexibility as summarized in Table I. The indicators of product and mix flexibility show the capability of a supplier for designing, testing and prototyping while the volume and delivery flexibility influence the efficiency of the design and development process. Design and production capability need to be considered together through the product life cycle.

TABLE I
FACTORS FOR SUPPLIER FLEXIBILITY

Dimension (No.)	No.	Indicator	Reference
Volume flexibility (C1)	C11	production capacity and facility	[39]
	C12	reserve capacity	[33]
Mix flexibility (C2)	C21	production line	[32]
	C22	set-up time	[34]
	C23	switching time	[34]
	C24	product variety	[34]

Dimension (No.)	No.	Indicator	Reference
Product flexibility (C3)	C31	technique and technology	[39], [40]
	C32	research and development	[40], [41]
	C33	dynamism of input technology	[40], [42]
	C34	manufacturing system	[35]
Delivery flexibility (C4)	C41	delivery reliability	[37]
	C42	transport mode	[38]

B. Power in supply chains

The power of party A over party B is defined as ‘the maximum potential ability of A to influence B in the system’ [12, 13]. According to power-dependence relation theory [8], power resides implicitly in the other’s dependence. The power of B over A is based upon the dependence of A on B. The need for resources, including financial and physical resources as well as information, makes an organization potentially dependent on its resource providers according to the resource dependence theory [7]. The dependence is determined by the importance of the resources to the organization and the concentration of the control of discretion over resources. For example, if the supplier intends to expand its business and it sees the potential business opportunities from the buyer, then the buyer possesses a certain amount of power over this supplier. Expertise, advanced technology, and special training from the buyer could also give buyer power over the supplier, which stems from a difference in knowledge. The dependence is usually asymmetric. If A depends more upon B than B depends upon A, then B has a power advantage over A [7, 8]. Dependence also holds the risk of supply defection, where one partner is free riding on others [43], i.e. not contributing to the value generation, holding-up their partners, using the position for better conditions[44], or creating leakage by syphoning off resources [45].

With suitable indicators power can be quantified. The power advantage of a buyer over a supplier implies to what extent the buyer can influence the supplier to accommodate its requests during the product life cycle. This is particularly important for introducing product innovation during product development, because the uncertainty is high, and design changes are highly iterative processes. To include power when assessing supplier helps make a rational decision. Power is a multi-dimensional construct like flexibility but often treated as a single criterion by researchers when assessing suppliers.

The most widely used model of power is Michael Porter's five forces model [46, 47], which points out that buyer power and supplier power are determined by several indicators. Based on Michael Porter's research, our research selects ten more highly cited articles to extract measurable indicators. Most of the selected articles are empirical studies on power in the supply chain except [9] and [23] that are conceptual studies. 18 power indicators are extracted, as shown in Table II. They are grouped as power from the external environment of the market (e.g. available alternative buyers/suppliers) and internal environment arising from the business or product (e.g. buyer's switching cost). The indicators are distinguished by whether they add to supplier power (indicated by 'SP' in Table I) or buyer power (indicated by 'BP' in Table I). Take indicator D10 'buyer's threat of integrating backward to the business' for example. 'No threat' means no power for buyer over the supplier regarding this indicator, and also no additional supplier power. But there are indicators that work in two ways. 'Purchased volume relative to supplier's sale' is such an indicator. Bigger value (denoted by \uparrow in the table) conveys more power to buyer but a smaller value (denoted by \downarrow), in the contrary, gives the supplier power. In this case ' $\uparrow \checkmark$ ' is marked under 'BP' and ' $\downarrow \checkmark$ ' is marked under 'SP' for this indicator.

TABLE II
INDICATORS FOR BUYER POWER AND SUPPLIER POWER

	No.	Indicator	SP	BP	Reference
External Environment	D1	Available alternative buyers	$\uparrow \checkmark$	$\downarrow \checkmark$	[46], [47], [23], [48], [9], [49], [50], [51], [52]
	D2	Available alternative suppliers	$\downarrow \checkmark$	$\uparrow \checkmark$	[46], [47], [23], [48], [49], [10], [52]
	D3	Buyer brand recognition		\checkmark	[53], [10]
	D4	Customer preference for supplier	\checkmark		[53], [10], [52]
Internal environment	D5	Buyer's switching cost (on supplier)	\checkmark		[46], [47], [23], [48], [9], [49], [50], [54], [10], [52]
	D6	Supplier's switching cost (on buyer)		\checkmark	[46], [47], [23], [48], [49], [54], [10], [52]
	D7	Purchased volume relative to supplier's sales	$\uparrow \checkmark$	$\downarrow \checkmark$	[53], [46], [47], [23], [48], [9], [49], [50], [54], [10], [51]
	D8	Impact on buyer's business (product differentiation)	\checkmark		[48]
	D9	Supplier's threat of integrating forward to the business	\checkmark		[46], [47], [23], [48]
	D10	Buyer's threat of integrating backward		\checkmark	[46], [47], [23], [48]

No.	Indicator	SP	BP	Reference
D11	Impact on buyer's cost structure	√		[48]
D12	Anticipated profits for supplier brought by buyer		√	[51]
D13	New business opportunity for supplier brought by buyer		√	[51]
D14	Differentiation of the product of supplier	√		[46], [47], [23], [54], [10]
D15	Importance to the quality of buyer's products or services	√		[46], [47]
D16	Dependence on supplier's expertise and knowledge	√		[53], [23], [49], [50], [54], [10], [52]
D17	Dependence on buyer's expertise and knowledge		√	[53], [49], [50], [54], [10]
D18	Dependence on supplier's reliable delivery	√		[53], [54], [10]

Power influences the behaviors or attitudes of buyer and supplier in terms of the leverage they have before and after establishing a relationship. For example, a powerful buyer could push suppliers to improve products and processes [15] or fostering the innovations it desired with its supply chain partners [16], while a powerful supplier could lower its provided performance [13, 14, 55].

C. The relations between power, trust, willingness, and commitment

An alternative conceptualization of power in supply chains is in terms of trust, willingness, and commitment with indicators overlapping to a certain extent (seen Table III).

TABLE III
EXAMPLE OF OVERLAPPING INDICATORS OF POWER, TRUST, WILLINGNESS, AND COMMITMENT

Concept	Indicator of the concept	Corresponding power indicator
Trust	Providing values to the partner [17]	D7, D12, D13
	Technique or capability of the partner [17, 18]	D16, D17
Willingness (to share/adoption)	Percentage sourced from emerging markets [56]	D7
	New business information [57]	D13
Commitment	How much one party is rewarded [19]	D12, D13
	The reason that one party prefers a partner to others is because of what this partner stands for [19, 20]	D3, D4

The measurement of trust, willingness, and commitment looks at the intrinsic motivation to collaboration mostly from the confidence in a partner's reliability and integrity, the perceived values and fair trade, and the

identification with a partner. It implies that none of the partners defects. By contrast power is derived from the relative dependence between partners (the need for each other). It impacts on trust, willingness, and commitment as illustrated in Fig. 2. Referent power from being an acknowledged leader or expert in the field increases the trust in the holder of the referent power [18] and the commitment to them [20], while power from punishment and legitimation limits these. Trust and commitment affect the willingness to share[57].

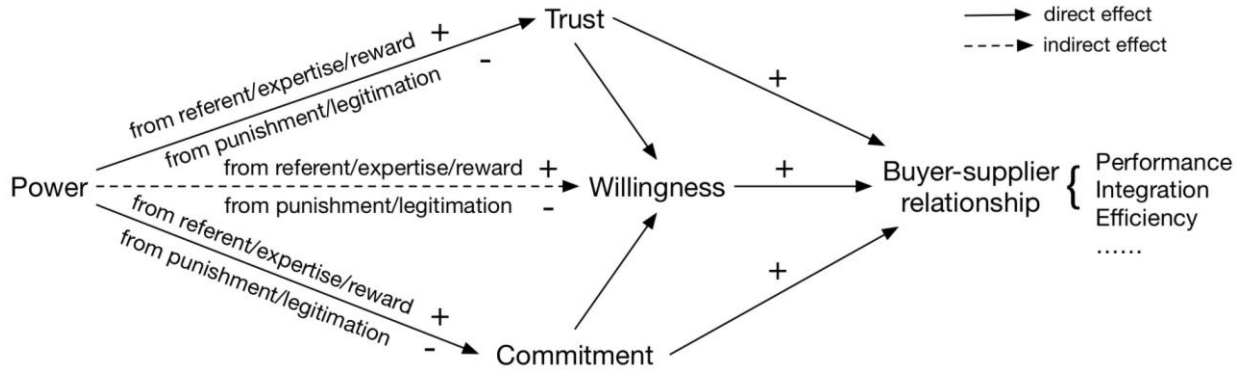


Fig. 2. The relations between power, trust/willingness, and commitment

Power is related to but also distinct from trust, willingness, and commitment. Power in some cases can be used by one party to induce desired actions of another party even if the other is not willing to compromise [21]. This is up to ‘potential ability of A to influence the decision of B’ and the ability of B to counter this influence. Power is conceptualized in this paper as an underlying issue that can be expressed through indicators.

III. AN EMPIRICAL STUDY ON POWER

The empirical study was carried out at a European company that designs and produces off-highway Diesel engines. For reasons of confidentiality, the company name is anonymous. It is an appropriate organization to study, because the engine company is both a buyer to parts and components and a first-tier supplier to many OEMs. Therefore it is able to provide views from both buyer and supplier perspectives. The company belongs to an international brand which supplies both the parent company and other brands. The company has facilities operating around the globe including North and South America, India, China, and the United Kingdom. It has distributors in 180 countries and 3,500 outlets, with a reliable delivery network for products

and services. For the study reported in the paper two interviews were carried out specifically on the supplier relations in the company, however the authors have been working over many years with company on other topics such as test planning [58], system architecture [59], and engineering change [60], where supply chain related issues have come up in numerous other interviews with product development engineers and test engineers who were responsible for quality assurance. The company used power as a high-level factor when assessing strategic suppliers. The company asks themselves questions like “*Are they bigger than us? Are they smaller than us? Will they listen to what we say or not? ... We look at where that supplier is and they look where we are. Each will take a stand and know what game to play.*” The case study focused on power.

A. Methodology

The evidence in this study was collected using semi-structured in-depth interviews. The main aim of the interviews was to study how power was understood from practice and how it affected practice in supply chain management. The results corroborate the lack of an effective quantitative assessment for power relationship.

Two interviews were conducted with a senior technical manager by the authors during February 2016 and April 2016. He was selected for the interviews, because he had extensive experience with the company in variety of roles including strategic roles. He had also collaborated on past studies on engineering change and system architecture design, which had frequently brought up issues of pushing and integrating innovation into diesel engines including the role of the suppliers. He was approached by email and provided a short summary of the objectives of the study in the course of setting up the interviews. He prepared a presentation on his view of power issues in supply chain relationships. The interviewers prepared a list of topics the authors wished to cover, but the interviewee was allowed to move the discussion onto related issues if it was necessary. Each interview lasted for more than 3 hours.

Our analysis draws upon two sources of data: (a) company materials including the presentation the interviewee prepared, and (b) the interviews. The analysis of the first interview raised more questions, which led to the second interview. The interviews were digitally recorded and subsequently transcribed. Recordings of both interviews were listened to several times to avoid overlooking important information. The data were

iteratively coded and analyzed where relevant text was selected according to the topics discussed in the interviews [61]. Outstanding points were clarified later by email exchanges with the interviewee. Quotes from the interviews are provided in italics with double quotation marks.

B. The need for flexibility and the classification of suppliers

The second author has worked with the same case study company for many years on engineering change, which frequently brought up issues of product flexibility. Diesel engines are highly interconnected products, so that a small change to one part of the system can have huge knock-on effects to other parts of the product [60]. While the company intends to reuse about 80% of their components between product generations, this is not always possible [59] and components need to be changed even if they have been frozen late in the product development process [62]. Many of the cast components, like the engine block, have very long lead time. Therefore, the company needs suppliers who are willing to make changes as and when required, in some cases several times during the product development process.

An engine has thousands of parts which are divided into standard parts and long lead time components such as major castings and control software. The company is mainly concerned with supplier relationships for these long lead time parts, because these components often contain significant intellectual property or are part of their product differentiation. Fig. 3 shows a simplified supply network of the company.

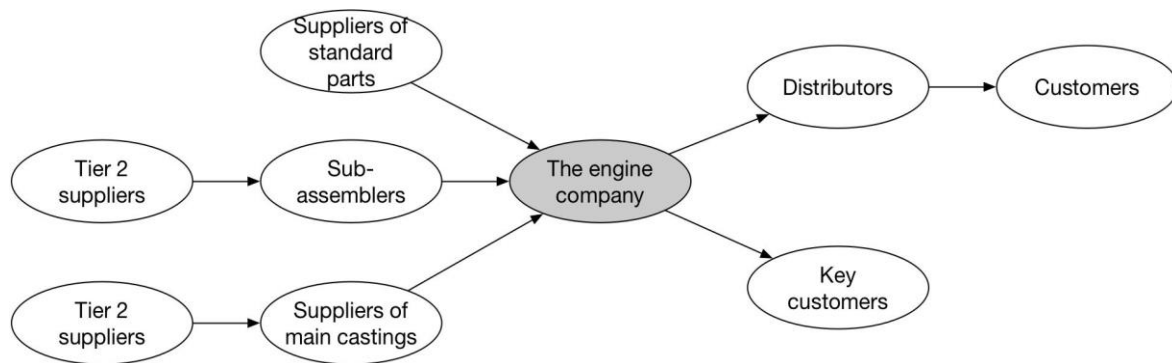


Fig. 3. The simplified supply network of the company

The company buys 70-80% of its components, therefore good performance such as on-time delivery and reliable quality is essential. The innovation and technology capacity of suppliers influence the design and

development process of new products, because it affects what is developed in house and how new parts are integrated with existing ones. The company gives great consideration to selecting strategic suppliers who are aligned with the company development strategy, collaborate with the company to identify the best design solutions, and share information with the company. *“Whereas with a strategic partner we would share with them forecast, the bad news and good news.... We've given out those capabilities back to our suppliers because they're the ones that can optimize that rather than telling them we want this feature.”* Strategic suppliers are rarely changed because of switching cost and available alternatives. *“We often get into that dilemma. Because the strategy is that and it was a little bit reluctant to change once we made a strategic decision even if the products coming up badly.”* Sometimes, capable suppliers may refuse to adjust their supply according to the company's forecast on sales or notify any changes in their process. Power plays a role in whether and how a supplier responds. *“We will go back to our supplier and say ‘is there any way you could increase your schedule in the next three months?’ If he says no, we take note of that. If he says ‘the best I can do is this. It's an open book that we have got these resources and here is what we can do for you. Is that acceptable?’ When it comes around power analysis, we take these things into consideration. Did they response to our request or didn't they?”*

C. Understanding power

The company has many well-established suppliers because the diesel engines are a mature technology. As more sensors and electronic technology are integrated in the engines, new suppliers are involved. *“There are not a lot of opportunities to change suppliers because we don't want to keep changing suppliers... The biggest opportunity to change them is when we introduce new product. That's our opportunity to say: do we use the same technology, do we have the correct suppliers today or shall we change them?”* Supplier selection is an iterative decision-making process, which brings up more factors with which to compare the existing and potential suppliers. Product innovation and development aligns the company's innovation and suppliers' capability. The engine company identifies the key technologies that add value to their market and then assesses whether a supplier of a particular technology has the capacity and ability to deliver the new

technology under acceptable cost. If the technology of a particular supplier adds value, the company might prefer this supplier, but whether they work with this supplier also depends on many other factors like its technological maturity, cost, and fit to the business strategy.

The company also needs them to be responsive to the changes during development process so as to meet the changing market. For example, the success of meeting the increased customer demand, to some extent, is determined on one hand by the production facility and capacity of the involved suppliers and on the other hand by the possibility of the suppliers to be flexible. This possibility implies the ability of the company to influence the suppliers in the way they need them to be, whilst there may be suppliers' resistance to this influence. It is to some extent a matter of power.

The company understands that power arises from need. *"Power is how important you are to that supplier. Either the supplier has a need of your business, or you have a need on your supplier."* The need initiates the dependence between the supplier and the company and gives rise to power. The company defines power as the purchased volume relative to supplier's sales. For the company this is an important issue, as the volumes in off-highway engines are much smaller than in automotive engines, which gives them little power over suppliers who supply both. As the interviewee claimed, *"There's a market out there for a billion units. If a supplier is serving a half billion of those, then you know he is the most powerful supplier, and your volume proportion of that is the way we look at it, as how much power we have. So if we're on servicing in a few hundred thousand units, we are not important to that supplier at all. Therefore, there is no reason why he should do anything rather than giving us a price that suits him for the inconvenience of doing this small volume."* For example, Beta (name is changed for confidentiality) is a global supplier of electronic control components and supplies up to 400,000 electronic control modules to the company a year. This is a high volume to the company as an off-highway engine manufacturer, but small compared to the order volumes for a platform product in the automotive industry. This volume takes up a very small proportion of Beta's whole market size. The engine company does not have a powerful position in this relationship. Relative purchased volume is also the way the company as a supplier perceives its customer's power. *"If this is Nu (name is*

changed for confidentiality) *who manufactures 50,000 machines and take 50,000 engines, that's a powerful customer. And we will do whatever is necessary to satisfy him.*" Beta, as an important player in the area, is also a leading innovator. This gives the company the option of taking innovations that Beta offer to them and accommodating them in their product or finding another supplier who might be more interested in developing technology with them. Having a small share of the market does not mean that a company like Beta is not interested in collaborating with the engine company on innovation, for example as a means to bringing an innovative technology to the market. However, Beta would be setting the terms. *"The power of a supplier also determines the type of contracts, expectations on cost recovery, on quality and so on."*

Though the company explicitly defined power as purchased volume relative to supplier's sales, they also mentioned other indicators. This validates power as a multi-dimensional construct (conforming to Table II), and indicates a need of a systematic way of assessing power in terms of multiple aspects.

- 1) Switching cost. When working with a casting supplier, *"we also look at this cost of switching..... So that casting supplier got power over us, knowing if we switch, they got three years before we are going to switch. Because we are not going to switch just like that, especially if they've got IP from tooling and we don't. Power is available to our supplier depending on how long it takes us to develop a new supplier."*
- 2) Available alternatives. The situation of having few alternatives also leads to a highly dependent relationship. *"When we came to emission technology, we have to use certain technologies and devices that only a few companies have. So you don't have lot of choices rather than go to those companies. Therefore, you are very dependent on some of those companies."*
- 3) Specific knowledge. In the days of fully mechanical engines the company used to design everything in the engine and knew the technologies and the way they performed in detail. When buying fully mechanical parts, like cylinder, the company can correct their suppliers. *"We can tell our head supplier: 'hey, you are making that cylinder too thin and it won't work'. They have to believe us because we know how they are going to work together. If they do casting, modulating and machining, we again can tell them 'you are not casting properly'."*

- 4) Brand. Though the company's power is limited as a subsidiary but as a brand, it is in some parts of the world better known than its parent company, for example, in India. *"- You got some power, some control back to your parent company. -Yes, because of brand."*
- 5) The importance of the company to its partner and vice versa. *"Either the supplier has a need of your business, or you have a need on your supplier. Power comes down to a need."* When a supplier does not perceive the power in the same way, the company makes them aware of this. *"Supplier may think they don't have a need on you but you need to convince them. You must work with us, look what we bring."*

D. Influence of power imbalance

Product innovation and development involves uncertainty, such as shifting demand, fluctuating cost, and changing technology. Sometimes, uncertainties are brought by suppliers, for example extra development cost, phase-out component and unexpected performance. The relative power between buyer and supplier influences the reaction of the company to uncertainty because it influences the response and attitude of the suppliers to the company's request. The consideration on this influence could further determine the company's choice of suppliers. The following presents examples of how the engine company coped with uncertainty with their suppliers and the responses under power imbalance.

- 1) Shift in volume. When there is a shift in the engine manufacturing volume, for example a doubling volume in the coming month, the company goes back to their suppliers and asks if they could increase their schedule in the next month. Beta, as a powerful supplier, probably will say *"sorry, we've an agreement. If you are not smart enough to tell us 6 months ahead, that's what you're getting."* But if the supplier is dependent on the company's business, the company can request the supplier to run on additional shifts to produce more components.
- 2) Excess cost. The company calculates the cost that component should be. If a supplier is selling the parts 10% above that, the company will require open book accounting to understand why the supplier charges so much. If it is due to an inefficient process, the company will try to work with the supplier to improve their process to reduce the cost. However, the company could not do that with big suppliers like Beta.

- 3) Component development cost. The company is going to bring out a new product. Customised ECMs (electronic control modules) will be purchased, which will require high investment. If a large customer requires a new ECM, Beta will absorb this development cost. But with the company, Beta will charge the development cost, which increases the total cost of the company.
- 4) Component phase-out. The company has received notice from Beta that they are thinking of replacing the provided type of ECM, because there is no other demand for this type of ECM. The typical way to solve the problem is to negotiate to maintain production at a certain level. But Beta left the company two choices, either moving to a higher volume product at the same cost or to pay twenty percent more for this ECM. *“That is the way they negotiate because they have the power to do that.”* This could lead to the problems on the customer side. *“If we’ve got a very powerful supplier insisting changing something. It’s a real problem with our customers.”*
- 5) Performance continuation. The company monitors the performance of the suppliers. When they notice Beta not performing as well as previously, the company notifies them but Beta might do nothing. But if it is a supplier dependent on the company, the supplier usually responds very quickly to sort the problem out.
- 6) New regional suppliers. When opening new manufacturing facilities in a new region, the company seeks new strategic partnership. Though Beta has already some manufacturing capabilities, the company might still prefer to develop a supplier rather than to work with Beta. The reason is because *“they can knock us around and tell us they are not manufacturing these and we have a sudden down turn of volume that will charge fortune and penalties.”*

When powerful suppliers expose the company to the risks of refused request and lowered performance, they are usually the capable suppliers. The company makes volume forecasts. Small suppliers rely on the prediction to plan recruitment, investment in machines, procuring raw materials, and setting up logistics. In case of changed demand, even if these suppliers are willing to respond but probably unable to fulfill the shift. Big companies like Beta produce millions of parts so that increasing the purchase volume, for example, from

40,000 to 50,000, does not cause a problem. But they are likely to be unwilling to service unexpected change. This presents a dilemma, choosing a capable supplier or a responsive supplier?

E. Complementary perspectives from additional interviews

Two additional interviews were also carried out in two independent companies [63]: a technical manager in charge of method introduction in a large electronics supplier to the automobile industry, who worked with multiple large brands; and the CEO of a small start-up designing and developing photosensitive chips for cameras. Both equated power with the relative size of a company, but also pointed out more indicators. The CEO of the chip company considered that technical expertise and opportunity to enter a new market gave them power. *“We don't have any power at the beginning of the negotiation or even the collaboration, but their need to enter the market gives us advantage. Though I still don't think we have power currently, showing them our design ability helps us find a position in the relationship. And once our products are widely accepted and ordered, we will have the capability for arguing more during the negotiation.”* The chip company selected the manufacturer as a supplier even before the design began, because each manufacturer has a set of rules that influence the design and the quality of the chips. Most big manufacturers were not interested in working with a start-up. The company finally managed to attract the biggest manufacturer by showing their background, products to be manufactured, strategic plan, customers, and market. This supplier was interested in entering the market the chip company was operating in and saw this as an opportunity to position themselves. The interviewee of the electronics supplier explained that power is important in crises, such as when delay, shortage or quality issues happened, because it enables the company to take control over part of their supplier's production phase or to shift the loss to its suppliers or customers. The two interviews also show that power comes from various aspects and influences the buyer-supplier relationship.

F. Conclusion

Flexible suppliers are competent to meet the company's demand and to provide what the company wants for product innovation and development. But those suppliers might not be willing to accommodate the requests. Arising from the dependence, power leads to each party, supplier and buyer, considering the other's

request and response to maintain a steady relationship. Powerful suppliers are less inclined to respond quickly to information requests or disclose information that does give them a competitive advantage. It is also hard to negotiate with them in terms of volume, cost, and quality. On the contrary, a less powerful partner would be willing to adapt to the changes. The relative power between buyer and supplier indicates the possibility that the supplier will respond to company's request. Though power was recognized by the company as an important aspect in collaboration, there seems no systematic tool to assess relative power. *"I don't believe we use power academically. Our power definition doesn't encompass everything power should."* – from the interviews in the engine company.

Assessing flexibility and power separately is not enough to determine whether a supplier is suitable to work with. Ideal suppliers are those who have high flexibility and who can be enticed to use this flexibility for the benefit of the company. We call this malleability, because it corresponds to the ability of the company to shape a supplier around their own needs. Malleable suppliers are those, who have limited power over the company and do not push back when companies demand changes but are able to deliver these changes. In this paper we develop a malleability index, which combines power and flexibility. For the purpose of this research we use the following definitions:

-- ***Flexibility***: the capability of supplier to meet various buyer requests (i.e. the capability of being flexible), such as production capacity and facility, production line, technology and delivery reliability.

-- ***Power***: the ability of one party to influence the other. The difference between buyer power and supplier power indicates the possibility that the supplier will respond to buyer request (i.e. the possibility of choosing to be flexible).

-- ***Malleability***: the potential of the supplier being willing and able to fulfill a request.

IV. THE ASSESSMENT MODEL FOR MALLEABILITY INDEX

A supplier of high flexibility and less power than the buyer is malleable, because it is likely to choose to be flexible. By contrast, a supplier of low flexibility but greater power than the buyer is not likely to be

malleable to the buyer's demands. This paper proposes a malleability index to measure the malleability of a supplier by combining flexibility and power.

A. The principles of the malleability index calculation

The calculation of the malleability index of each supplier uses a TOPSIS approach. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) proposed by Hwang and Yoon [64] is a compromise decision-making method, choosing the solution closest to the best case scenario and furthest from the worst one. It provides a result within a range of [0,1]. The extremes for malleability are:

-- **Best Case Scenario for Malleability (BCS):** The supplier has extremely high flexibility while the buyer has extreme power advantage over it.

-- **Worst Case Scenario for Malleability (WCS):** The supplier has extremely low flexibility and extreme power advantage over the buyer.

The values of flexibility and power advantage are the inputs to TOPSIS, so they need to be assessed first. As shown in Fig. 4, a group of suppliers are assessed for their flexibility against a number of flexibility indicators. The weights of these indicators combined with the calculations of supplier performance against each indicator provide the value of flexibility. The assessment of power advantage is relational, looking at the interplay between buyer and supplier. The power indicators for the buyer and the supplier are weighted. The power advantage is calculated as the difference between the buyer power and the supplier power. The details of the calculation are presented in the following sections.

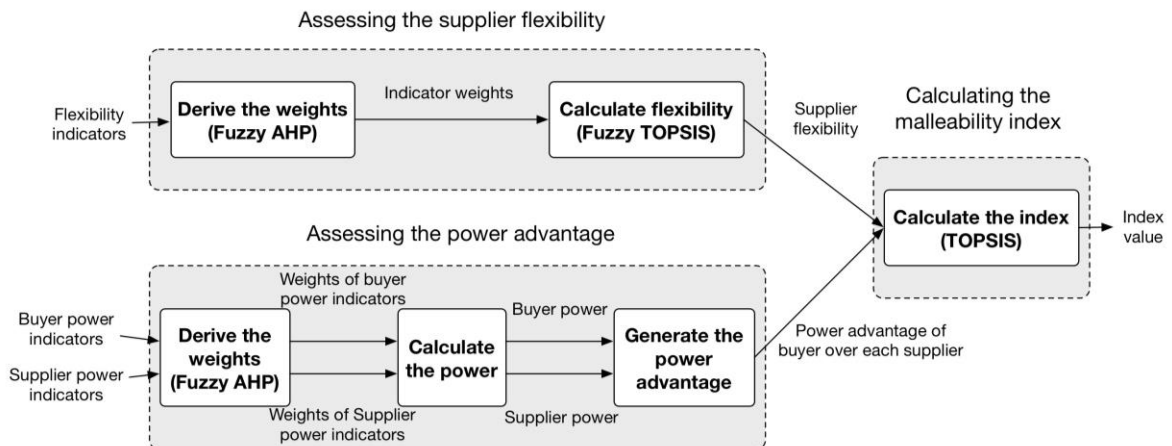


Fig. 4. The assessment logic of the tool for malleability index

In this paper, we assume that all potential suppliers are measured against the same sets of indicators as discussed in section II, but the tool allows the user to customize the sets (selecting, adding or removing indicators for the application).

B. Assessing the supplier flexibility and the power advantage

Both flexibility and power advantage assessments have weighted indicators to reflect the company's priorities. For example, technique and technology (indicator C31 in Table I) is likely to be more important than reserve capacity (C21) for supplier flexibility since it has direct impact on product innovation. Similarly, purchased volume relative to supplier's sales (indicator D7 in Table II) contributes more to buyer power than buyer brand (D3). This section presents first how the weights of indicators are derived and then explains the assessment methods for flexibility and for power advantage.

1) Deriving the weights of indicators

Fuzzy Analytic Hierarchy Process (AHP) has been chosen for the weight calculation. AHP proposed by Saaty [65] is a widely used multi-criteria decision-making method. It outperforms other decision-making methods by ease of use, structuring the problem systematically, and calculating indicator weights as well as alternative priorities. AHP structures a problem in a hierarchical way, descending from a goal to criteria, sub-criteria and alternatives in successive levels. The hierarchy provides the users with an overall view of the complex relationships inherent in the context; and helps them to assess whether the elements of the same level are comparable. The elements are then pairwise compared according to 9 level-scales to derive their weights. AHP allows verbal judgements for pairwise comparison which might introduce imprecision. As a popular methodology for handling imprecision, fuzzy set theory proposed by Zadeh [66] is combined with AHP to give fuzzy AHP. A fuzzy set consists of two components, a set of elements x and an associated membership function $\mu(x)$. Triangular fuzzy numbers (TFNs) \tilde{A} , a special class of fuzzy set, is used in this paper. It can be expressed as a triple (l, m, h) where l and h are the least and largest values respectively with the smallest membership degrees and m is the value with the largest membership to the set. The membership function of a TFN is defined as follows and illustrated in Fig. 5.

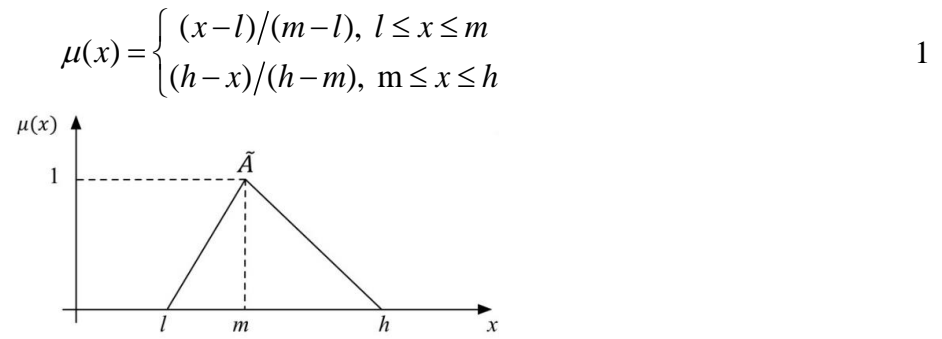


Fig. 5. A TFN

TFNs capture the linguistic terms describing the relative importance of an indicator over another. Table IV lists the linguistic terms with their corresponding TFNs.

TABLE IV
JUDGMENT SCALE FOR RELATIVE IMPORTANCE

<i>Importance definition</i>	<i>TFNs</i>
Extremely more important (ES)	(8,9,9)
Intermediate (VVS)	(7,8,9)
Very strongly more important (VS)	(6,7,8)
Intermediate (S+)	(5,6,7)
Strongly more important (S)	(4,5,6)
Intermediate (M+)	(3,4,5)
Moderately more important (M)	(2,3,4)
Intermediate (W)	(1,2,3)
Equally important (E)	(1,1,1)

The first step of calculating the weights is to establish the fuzzy pairwise comparison matrix. The judgments are then synthesized, if there are multiple decision makers. The fuzzy weight of each indicator is derived from the synthesized fuzzy pairwise comparison matrix by the geometric mean, which combines the relative importance of an indicator over all the others. The applicability of the geometric mean for synthesis and derivation of weight from the matrix has been proven ([67] and [68]). Though fuzzy values deal with imprecision, crisp values are more intuitive for comparison. Therefore, the fuzzy weights are transformed to single values by the centroid method [69] as the crisp weights. The details of the calculation steps and equations are presented in Appendix A.

2) Assessing the supplier flexibility

The assessment of supplier flexibility is based on an estimation of the suppliers' performance against the indicators of volume, mix, product, and delivery flexibility as listed in Table I. These indicators are

weighted first, and then the suppliers are compared for flexibility. Though fuzzy AHP is also able to calculate the flexibility, this paper chooses fuzzy TOPSIS. TOPSIS is based on comparisons to worst and best cases instead of pairwise comparisons. It requires less computational effort. With m suppliers and n criteria, AHP has a computational complexity of $m^2 \times n$. TOPSIS has a computational complexity of $m \times n$.

Fuzzy TOPSIS is the fuzzy extension of TOPSIS where fuzzy sets are used. There are two types of values during the assessment. One is the numeric value for a quantitative indicator, e.g. 15 days for set-up time; the other is subjective judgement such as ‘high’, ‘medium’, and ‘low’ for a qualitative indicator. However, most fuzzy TOPSIS models take fuzzy numbers for all indicators, which leads to numeric values being ignored. We choose the fuzzy TOPSIS model proposed by Liu et al. [25] which considers both types. The details of the calculation steps and equations are presented in Appendix B. It is noted that flexibility indicators are distinguished by benefit (the larger the value the better) and cost (the smaller the value the better). Table V lists the linguistic terms for judgements with their corresponding TFNs.

TABLE V
JUDGMENT SCALE FOR FLEXIBILITY AND POWER

<i>TFNs for flexibility judgement</i>			<i>Scale for power judgment</i>	
<i>Linguistic expressions</i>	<i>TFNs for benefit indicator</i>	<i>TFNs for cost indicator</i>	<i>Linguistic expressions</i>	<i>TFNs for power</i>
Extremely high (EH)	(7,8,8)	(0,0,1)	Extremely high (EH)	(7,8,8)
Very high (VH)	(6,7,8)	(0,1,2)	Very high (VH)	(6,7,8)
High (H)	(5,6,7)	(1,2,3)	High (H)	(5,6,7)
Medium high (MH)	(4,5,6)	(2,3,4)	Medium high (MH)	(4,5,6)
Medium (M)	(3,4,5)	(3,4,5)	Medium (M)	(3,4,5)
Medium low (ML)	(2,3,4)	(4,5,6)	Medium low (ML)	(2,3,4)
Low (L)	(1,2,3)	(5,6,7)	Low (L)	(1,2,3)
Very low (VL)	(0,1,2)	(6,7,8)	Very low (VL)	(0,1,2)
Extremely low (EL)	(0,0,1)	(7,8,8)	Extremely low (EL)	(0,0,1)

3) Assessing the power advantage

Power advantage is determined by calculating both buyer and supplier power. Various power indicators need to be considered for a full analysis of power as discussed in the literature and empirical case. Buyer power varies with respect to different suppliers. For example, the purchased volume relative to supplier's sales depends on its purchase from a particular supplier and the total sales of this supplier. The procedure for

calculation of buyer power regarding a particular supplier is presented. The power of a particular supplier regarding the buyer is calculated in the same way.

-- *Step 1: Determine the power indicators.* Power indicators are gathered for buyer and supplier respectively. For those indicators that work in the two ways as listed in Table II, the decision makers have to reflect whether the indicator adds up to the buyer power or the supplier power.

-- *Step 2: Determine the weights of power indicators.* The weights are calculated by fuzzy AHP as explained in the previous section.

-- *Step 3: Establish decision matrix $D = [\tilde{p}_{ij}]_{q \times n}$.* Let q be the number of decision makers and n the number of buyer power indicators. The entry $\tilde{p}_{ij} = (l_{ij}, m_{ij}, h_{ij})$ is a TFN representing the judgment of decision maker i on how much power the buyer has regarding indicator j . The scale of weights in Table II is used.

-- *Step 4: Synthesize the multiple judgments.* The synthesized buyer power against indicator j , denoted as \tilde{p}_j , is:

$$\tilde{p}_j = (l_j, m_j, h_j) = ((\prod_{i=1}^q l_{ij})^{\frac{1}{q}}, (\prod_{i=1}^q m_{ij})^{\frac{1}{q}}, (\prod_{i=1}^q h_{ij})^{\frac{1}{q}}) \quad 2$$

-- *Step 5: Compute the overall buyer power.* It is the sum of the buyer power against each indicator by combining the indicator weights. BP is the fuzzy overall buyer power value and BP is the crisp value for further comparison.

$$BP = (l, m, n) = \sum_{j=1}^n w_j \times \tilde{p}_j = (\sum_{j=1}^n w_j \times l_j, \sum_{j=1}^n w_j \times m_j, \sum_{j=1}^n w_j \times h_j) \quad 3$$

$$BP = (l + 2m + h) / 4$$

The supplier power SP is calculated by repeating the steps 1 to 5. The power advantage of the buyer over a particular supplier, denoted as $PA(buyer/supplier)$, is generated:

$$PA(buyer/supplier) = BP - SP \quad 4$$

Three cases exist for $PA(buyer/supplier)$:

- Buyer domination: $PA(buyer/supplier) > 0$
- Equilibrium: $PA(buyer/supplier) = 0$

-- Supplier domination: $PA(buyer/supplier) < 0$

C. Calculating the malleability index by integrating flexibility and power

The malleability index of a supplier is the result of integrating its flexibility and the power advantage of buyer over it. TOPSIS calculates the index as follows.

-- *Step 1: Establish flexibility-power advantage matrix* $M = [x_{ij}]_{m \times 2}$. Let m be the number of suppliers with the two attributes (i.e. flexibility and power advantage). x_{i1} is the flexibility value of supplier i and x_{i2} is the power advantage value of the buyer over supplier i .

-- *Step 2: Normalize the matrix* $N = [r_{ij}]_{m \times n}$. Linear normalization as equation 7 is used to transform the two attributes into dimensionless quantities r_{ij} . The normalized values do not depend on their units so that they are comparable. Let x_j^* be the largest possible value of attribute j and x_j^- is the smallest possible value. r_{ij} is the normalized value of x_{ij} , which is a value within $[0,1]$.

$$r_{ij} = (x_{ij} - x_j^-) / (x_j^* - x_j^-), i = 1, 2, \dots, m, j = 1, 2 \quad 5$$

-- *Step 3: Determine BCS and WCS*. BCS is an ideal malleable supplier that has extremely high flexibility but is extremely dominated by the buyer. BCS has the largest possible values of the attributes which are 1 after normalization. By contrast, WCS contains the smallest normalized values, i.e. 0.

$$\begin{aligned} BCS &= \{1, 1\} \\ WCS &= \{0, 0\} \end{aligned} \quad 6$$

-- *Step 4: Calculate the distances to ideal cases*. D_i^+ and D_i^- are the distances of supplier i to BCS and WCS respectively. The results are:

$$\begin{aligned} D_i^+ &= \sqrt{\sum_{j=1}^2 (r_{ij} - 1)^2} \\ D_i^- &= \sqrt{\sum_{j=1}^2 (r_{ij} - 0)^2} = \sqrt{\sum_{j=1}^2 r_{ij}^2} \end{aligned} \quad 7$$

-- *Step 5: Calculate the malleability index*. The index of supplier i , MI_i , is based on its relative closeness to the BCS, as equation 10.

$$MI_i = D_i^- / (D_i^+ + D_i^-) \quad 8$$

It is a value between 0 and 1, which indicates the closeness to BCS. The closer to 1, the greater the malleability of the supplier. The closer to 0, the worse the malleability. When the value lies in the middle, it indicates a balance between the best and the worst. The unite interval $[0,1]$ is divided into three ranges and a supplier's malleability is as follows. 0.5 is the middle point of the unit interval. We consider $[0.45, 0.55)$ equal to middle by using the rule of rounding.

-- Good, if $MI_i \in [0.55, 0.6]$

-- Medium, if $MI_i \in [0.45, 0.55)$

-- Poor, if $MI_i \in [0, 0.45)$

The combination of fuzzy AHP-TOPSIS is suitable for supplier assessment, because some indicators are qualitative with subjective data and the use of TFNs deals with them. The method works for flexibility and power assessments separately as well as their integrated assessment, so that decision makers can compare the results (i.e. without and with malleability index).

V. ILLUSTRATIVE EXAMPLE

This section presents an illustrative example to demonstrate the proposed tool. The example is constructed based on the empirical study by amalgamating multiple examples discussed in the interviews. The buyer company FC is going to bring out a new product to the market and seeking strategic supplier for customized electronic control modules (ECM). Three potential suppliers are available. Supplier S1 is a newly founded local company with manufacturing facilities and offers a good price. However, FC has never worked with S1. Supplier S2 is a big company whose business covers a range of fields, like supplier Beta of the engine company. It has ready-made manufacturing facilities and its own market. Based on the collaboration history, FC knows that S2 is capable of providing high quality products but hard to negotiate with on issues such as price and delivery and would not absorb the development cost. Supplier S3 is a relatively big company which has been established for a long time, like supplier Delta. FC, as one of its main clients, has received stable performance from S3. The problem is that S3 does not have local manufacturing facilities. To sourcing from

its nearby plants will lead to high logistics cost. The tool assesses the malleability indices of these suppliers to determine a suitable partner.

A. Assessing the supplier flexibility

Supplier flexibility is assessed in terms of the four major dimensions discussed in section II: volume flexibility, mix flexibility, product flexibility, and delivery flexibility. Mix and product flexibilities are more important because the capability to customize the ECM is key to develop the new product. The cost to work with the suppliers need to be acceptable, thus the offered price and the logistics cost are also included in the assessment. Two decision makers (DM1 and DM2) participate in the decision process, pairwise comparing the indicators and estimating supplier performance under each indicator. Fig. 6 shows the comparison matrices and the weights of indicators calculated by Fuzzy AHP.

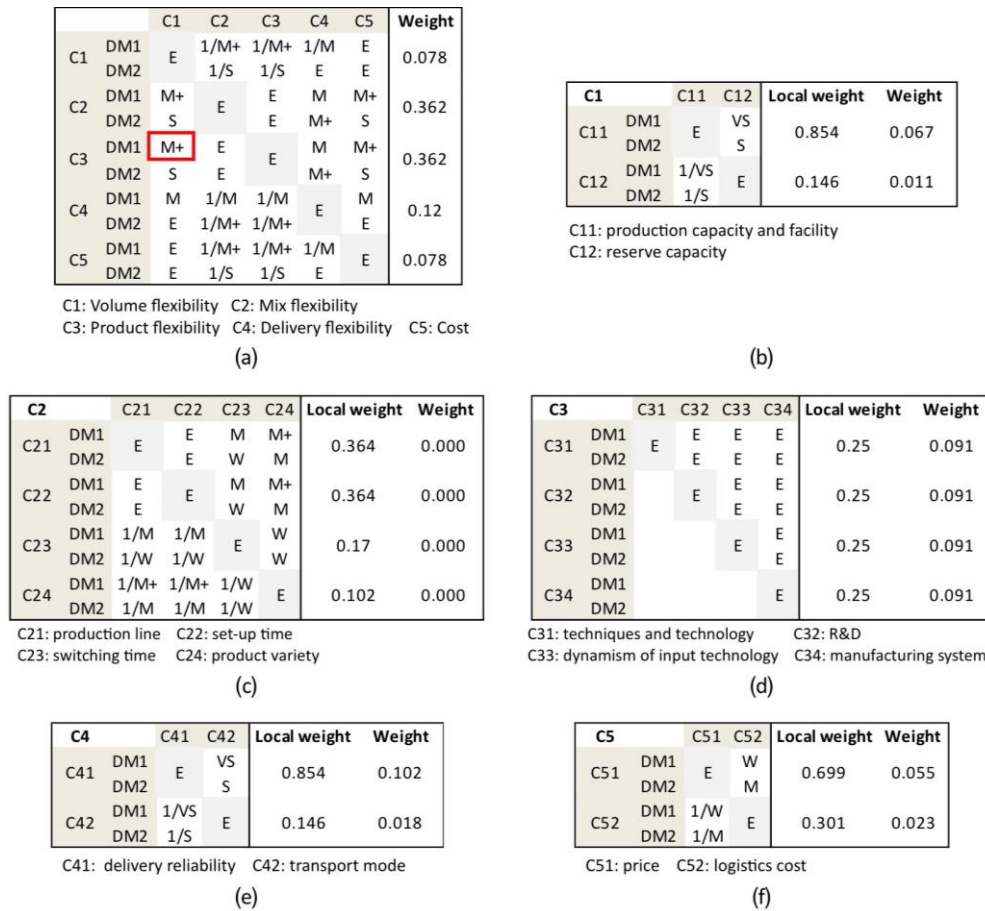


Fig. 6. Pairwise comparisons and weights of (a) the five dimensions, (b) the indicators under volume flexibility, (c) the indicators under mix flexibility, (d) indicators under product flexibility, (e) indicators under delivery flexibility, and (f) cost

C1 to C4 correspond to the four dimensions of flexibility in Table I (also noted below the matrices in Fig. 6) and C5 is the cost. C11 to C52 represent the indicators in each dimension and the cost as well. The entry is the verbal judgement of the relative importance of one indicator over another. Take the highlighted entry ‘M+’ in matrix (a) for example. It means that C3 (product flexibility) is more important than C1 (volume flexibility) and according to Table IV, the extent of this greater importance is ‘intermediate between moderately and strongly more important’.

The perspectives of the two decision makers are aggregated by equation A-1. The fuzzy weights are calculated by equation A-2 and translated to crisp weights by equation A-3. The flexibility of each supplier is then assessed by fuzzy TOPSIS. The decision matrix is established as shown in Fig. 7 (a). S1 to S3 are the three suppliers. The last two columns are the best and worst flexible situations. The entries are the judgements of the decision makers and are further transformed to TFNs referring to Table V. For example, the highlighted entry ‘MH’ stands for that DM1 considers S1’s technique and technology (C31) medium high (MH). The corresponding TFN is $\tilde{5} = (4,5,6)$. The decision matrix of the synthesized opinions is shown in Fig. 7 (b). This matrix is then normalized and accommodated with the weights of the flexibility indicators.

		S1		S2		S3		Best	Worst
		DM1	DM2	DM1	DM2	DM1	DM2	flexibility	flexibility
C1	C11	M	ML	VH	VH	H	MH	EH	EL
	C12	ML	L	VH	H	VH	H	EH	EL
	C21	M	ML	VH	VH	H	H	EH	EL
C2	C22	L	ML	L	ML	ML	M	EL	EH
	C23	M	MH	L	L	L	ML	EL	EH
	C24	L	L	VH	H	VH	H	EH	EL
C3	C31	MH	M	VH	VH	VH	H	EH	EL
	C32	M	ML	VH	VH	VH	H	EH	EL
	C33	M	M	H	H	VH	H	EH	EL
C4	C34	M	ML	VH	VH	VH	H	EH	EL
	C41	MH	MH	H	H	MH	M	EH	EL
	C42	H	MH	H	H	H	MH	EH	EL
C5	C51	L	L	MH	H	ML	M	EL	EH
	C52	L	VL	ML	ML	H	VH	EL	EH

(a)

		S1		S2		S3		Best	Worst
								flexibility	flexibility
C1	C11	(2.45, 3.46, 4.47)	(6, 7, 8)	(4.47, 5.48, 6.48)	(7,8,8)	(0,0,1)			
	C12	(1.41, 2.45, 3.46)	(5.48, 6.48, 7.48)	(5.48, 6.48, 7.48)	(7,8,8)	(0,0,1)			
	C21	(2.45, 3.46, 4.47)	(6, 7, 8)	(5, 6, 7)	(7,8,8)	(0,0,1)			
C2	C22	(4.47, 5.48, 6.48)	(4.47, 5.48, 6.48)	(3.46, 4.47, 5.48)	(7,8,8)	(0,0,1)			
	C23	(2.45, 3.46, 4.47)	(5, 6, 7)	(4.47, 5.48, 6.48)	(7,8,8)	(0,0,1)			
	C24	(1, 2, 3)	(5.48, 6.48, 7.48)	(5.48, 6.48, 7.48)	(7,8,8)	(0,0,1)			
C3	C31	(3.46, 4.47, 5.48)	(6, 7, 8)	(5.48, 6.48, 7.48)	(7,8,8)	(0,0,1)			
	C32	(2.45, 3.46, 4.47)	(6, 7, 8)	(5.48, 6.48, 7.48)	(7,8,8)	(0,0,1)			
	C33	(3, 4, 5)	(5, 6, 7)	(5.48, 6.48, 7.48)	(7,8,8)	(0,0,1)			
C4	C34	(2.45, 3.46, 4.47)	(6, 7, 8)	(5.48, 6.48, 7.48)	(7,8,8)	(0,0,1)			
	C41	(4, 5, 6)	(5, 6, 7)	(3.46, 4.47, 5.48)	(7,8,8)	(0,0,1)			
	C42	(4.47, 5.48, 6.48)	(5, 6, 7)	(4.47, 5.48, 6.48)	(7,8,8)	(0,0,1)			
C5	C51	(5, 6, 7)	(1.41, 2.45, 3.46)	(3.46, 4.47, 5.48)	(7,8,8)	(0,0,1)			
	C52	(5.48, 6.48, 7.48)	(4, 5, 6)	(0, 1.41, 2.45)	(7,8,8)	(0,0,1)			

(b)

Fig. 7. Establishing the decision matrix for flexibility: (a) of multiple opinions, and (b) of synthesized opinion

The distances to the best and worst flexible situations of each supplier are calculated by equation A-6 and the flexibility of each supplier is computed by equation A-7. The final results are shown in Table VI.

TABLE VI
FLEXIBILITY ASSESSMENT RESULT

	F^+	F^-	Flexibility	Category	Rank
S1	3.500	3.901	0.527	Medium	3
S2	1.560	5.895	0.791	High	1
S3	2.161	5.263	0.709	High	2

The flexibility order of the three suppliers is $S2 > S3 > S1$ where S2 and S3 are close to each other and much better than S1.

B. Assessing the power advantage

Greater power advantage of buyer over supplier indicates bigger possibility that a supplier would compromise. The power indicators in Table II are used and their weights are calculated first by fuzzy AHP. Table VII shows the weights.

TABLE VII
POWER INDICATORS AND THEIR WEIGHTS

<i>Buyer power</i>			<i>Supplier power</i>		
No.	Indicator	Weight	No.	Indicator	Weight
D1	Available alternative buyers	0.1049	D2	Available alternative suppliers	0.0626
D6	Purchased volume relative to supplier's sales	0.3378	D7	Importance to buyer's business	0.2981
D11	Anticipated profits for supplier brought by buyer	0.2347	D10	Impact on buyer's cost structure	0.025
D12	New business opportunity for supplier brought by buyer	0.1643	D5	Buyer's switching cost (on supplier)	0.097
D16	Dependence on buyer expertise & knowledge	0.0981	D13	Differentiation of the product of supplier	0.2097
D9	Buyer's threat of integrating backward	0.0302	D14	Importance to the quality of buyer's products or services	0.0614
D3	Customer recognition on buyer	0.0302	D17	Dependence on supplier reliable delivery	0.0391
			D15	Dependence on supplier expertise & knowledge	0.143
			D4	Customer preference on supplier	0.0391
			D8	Supplier's threat of integrating forward to the business	0.025

The power of FC varies with the three suppliers because the values regarding an indicator of buyer power would be different. Fig. 8 presents the decision matrices for the power of FC over each supplier (denoted by

BP_{Si}) and the power of each supplier over FC (denoted by SP_{Si}). The entry in each matrix is the judgement of a decision maker on how much power an indicator gives. For example, ‘L’ in the highlighted entry of matrix (a) means that FC has low power over S1 with respect to the indicator D1, judged by DM1.

BP_{s1}	D1	D6	D11	D16	D9	D3
DM1	L	VH	VH	VH	MH	H
DM2	ML	VH	VH	VH	H	H
(a)						
BP_{s2}	D1	D6	D11	D16	D9	D3
DM1	MH	L	L	ML	VL	H
DM2	H	L	L	M	VL	H
(c)						
BP_{s3}	D1	D6	D11	D16	D9	D3
DM1	M	H	H	EH	H	H
DM2	M	H	H	EH	H	H
(e)						

SP_{s1}	D2	D7	D10	D5	D13	D14	D17	D15	D4	D8
DM1	M	VH	M	MH	H	MH	M	ML	L	VL
DM2	M	VH	M	MH	H	MH	M	ML	L	VL
(b)										
SP_{s2}	D2	D7	D10	D5	D13	D14	D17	D15	D4	D8
DM1	M	VH	M	ML	H	MH	M	MH	H	M
DM2	M	VH	M	M	H	MH	M	MH	H	M
(d)										
SP_{s3}	D2	D7	D10	D5	D13	D14	D17	D15	D4	D8
DM1	M	VH	M	ML	H	MH	H	ML	M	L
DM2	M	VH	M	ML	H	MH	H	ML	M	L
(f)										

Fig. 8. Decision matrix of (a) BP_{S1} , (b) SP_{S1} , (c) BP_{S2} , (d) SP_{S2} , (e) BP_{S3} , and (f) SP_{S3}

BP_{Si} and SP_{Si} are calculated respectively by equation 3, where the estimations of the two decision makers are synthesized first by equation 2. The power advantage of FC over each supplier, $PA(FC/Si)$ is obtained by equation 4. The results are shown in Table VIII.

TABLE VIII					
POWER ADVANTAGE ASSESSMENT RESULT					
	BP	SP	PA	Category	Rank
S1	6.314	5.592	0.722	Buyer domination	1
S2	2.749	5.969	-3.211	Supplier domination	3
S3	6.079	5.787	0.292	Equilibrium	2

The preference order of the three suppliers is $S1 > S3 > S2$.

C. Calculating the malleability index

The malleability index supports the choice by balancing the flexibility and power advantage. The decision matrix is established and normalized by equation 5, as illustrated in Fig.6 (a) and (b) respectively. The values in Fig. 9 (a) are the calculation results from the previous two assessments. The last two rows show the BCS and the WCS. According equation A-7, the best flexibility value is 1 and the worst is 0. The case of the largest power is where the judgements under all the power indicators are ‘extremely high’, i.e. (7,8,8) in Table V while the case of the least power is that of ‘extremely low’. The largest and smallest power values

after defuzzification are 7.75 and 0.25 respectively. According to equation 4, the largest power advantage is 7.5 and the smallest is -7.5.

	Flexibility	PA(FC/Supplier)
S1	0.527	0.722
S2	0.791	-3.211
S3	0.709	0.292
BCS	1	7.5
WCS	0	-7.5

(a)

	Flexibility	PA(FC/Supplier)
S1	0.527	0.548
S2	0.791	0.286
S3	0.709	0.519
BCS	1	1
WCS	0	0

(b)

Fig. 9. Matrix for malleability assessment: (a) Decision matrix, and (b) Normalized decision matrix

The distances of each supplier to the BCS and the WCS are calculated by equation 7 and the malleability index (MI) is obtained by equation 8. Table IX present the results. S3 is malleable, the index value of which is much higher than the medium value 0.5. S1 and S2 are of medium malleability.

TABLE IX
MALLEABILITY INDEX VALUES

	D^*	D^-	MI	Category	Rank
S1	0.654	0.760	0.538	Medium	2
S2	0.744	0.841	0.531	Medium	3
S3	0.562	0.879	0.610	Good	1

D. Implications from the example

Only judging by the flexibility assessment, S2 is the best as they have the highest score in flexibility. This means that S2 has the highest capability to fulfill various and changing requests. If looking at the power relation with FC, the company holds the advantage over FC, which implies the risk of S2 not choosing to delivery on its flexibility like supplier Beta to the engine company in section III. If regarding the power assessment result, S1 seems the best choice but S1 might fail in responding to changes. The choice presents a dilemma. The malleability index allows a balanced choice.

From Table VI, that S3 has a good malleability index (also the largest among the three) indicates that it has the potential to be willing to fulfill the various requests from FC. On one hand, it has good flexibility (0.709); on the other, the power relationship between it and FC is balanced with the tendency of FC dominating S3 (PA : 0.292). S3 is a suitable choice for strategic collaboration. Especially, FC and S3 has high mutual

dependence (i.e. BP_A : 6.079 and SP_A : 5.787), which corresponds to the research results in [14] that under mutual dependence a long-term operational relationship should be established with extensive and close working. Considering the weak points in S3's flexibility, for example, no local manufacturing facilities, FC could develop and invest S3. However, this will increase the switching cost of FC on S3 and then leads to an increase of S3's power. As a result, the power advantage of FC over S3 would be reduced. This change could be overcome by increasing the dependence of S3 on FC for purchase volume and business opportunity. In addition, keeping S1 as a backup supplier reduces the switching cost and the time to set up production, and further raises buyer power. Applying the proposed tool before and after establishing the relationship can track the state of suppliers.

VI. CONCLUSION

The uncertainty during product innovation and development pushes companies to seek flexible suppliers who are capable to respond their requests. However, how a supplier responds also depends on who is more powerful, the supplier or the buyer. This power situation is difficult to assess due to its dependence on two sides and the variety of power indicators. Both literature and the case study company realize the importance of understanding power in working with suppliers but lack a tool to assess suppliers explicitly taking into power account. A tool helps because it formalizes explicitly the means by which a company knows why a supplier is recommended. Decision makers can then use this in making their final decisions.

This research proposes a malleability index for supplier assessment that integrates flexibility and power. Introducing this index offers not only a convenient way to assure the selected suppliers are competent and cooperative, but also makes companies to reflect over their emphasis on suppliers for product development and innovation. A decision tool based on fuzzy AHP and TOPSIS is developed for the assessments, which considers various flexibility dimensions and indicators for buyer and supplier power. It calculates the malleability index for each supplier and labels a supplier with its malleability as good, medium or poor, so that the companies can look into a particular supplier and rank all potential suppliers to choose a malleable

partner. The tool also deals with the mix of objective/subjective numeric and verbal information and multiple opinions of decision makers and has a straightforward underlying logic.

This research is positioned in new product development. The indicators can also be used in the entire supply chain management process for innovative products, because such types of product have a much higher uncertainty and risk in market demand, relative to functional products. The proposed malleability index also helps evaluate the malleability of a supplier for general selection and development. But the priorities placed on the indicators will be different while the fuzzy AHP methods allow appropriate adjustments.

This paper focuses on supplier flexibility because frequent changes is a distinctive feature of new product development. Flexibility assessment helps companies understand whether and by how much a supplier can be flexible. The proposed assessment method is also applicable to a wider range of criteria such as economic and management aspects which could be included in an overall performance assessment. Both performance and flexibility assessments are multiple-criteria decision-making problems, where there are qualitative and quantitative criteria and subjective and objective data.

The power analysis helps companies assess the possibility that a flexible supplier would choose to deliver on its flexibility. It also gives a company the potential to increase its power (or reduce its supplier's power) because the power indicators show the sources of power. For example, the company can enlarge its purchased volume, which adds to the company's power. It could try to get more backup suppliers because the situation of few available suppliers gives a supplier power. The company could also show a supplier more business opportunities, especially if the supplier does not realize this. It would also be interesting to understand how the supplier/buyer could behave and the underlying reasons under different power situations. For example, when both supplier and buyer have great power, it is not clear whether the supplier will choose to be flexible or not. This might depend on how important this buyer is to the supplier's business and it is worth doing further empirical studies.

This research limits the scope of the power analysis to a dyadic relation between buyer and supplier. The intervention of a third party could also influence the power advantage of buyer over supplier, such as the

power relation between the suppliers themselves or the help from a big customer. Another strand of future work would investigate the impacts of a third party on the power distributions. This further suggests considerations of power propagations along the supply network. For example, if the company has power over customer C and customer C has power over supplier A, does the company have a power over supplier A? It would be interesting to analyze this propagation and its implications for assessing suppliers.

APPENDIX

A. The calculation steps for the weights of indicators

-- *Step 1: Establish the $n \times n$ fuzzy pairwise comparison matrix $F = [\tilde{c}_{ij}]_{n \times n}$.* n is the number of the indicators. The entry $\tilde{c}_{ij} = (l_{ij}, m_{ij}, h_{ij})$ is TFN. It represents the judgement of the decision maker on the relative importance of indicator i over j . According to AHP, the relative importance of indicator j over i is $1/\tilde{c}_{ij}$.

-- *Step 2: Synthesize the judgments if there are multiple decision makers.* Let $\tilde{c}_{ij}^t = (l_{ij}^t, m_{ij}^t, h_{ij}^t)$ be the relative importance of criterion i over j judged by decision maker t . The multiple judgments towards the comparison of i over j need to be synthesized. Equation A-1 is used, where q is the number of the decision makers.

$$\tilde{c}_{ij} = (l_{ij}, m_{ij}, h_{ij}) = ((\prod_{t=1}^q l_{ij}^t)^{\frac{1}{q}}, (\prod_{t=1}^q m_{ij}^t)^{\frac{1}{q}}, (\prod_{t=1}^q h_{ij}^t)^{\frac{1}{q}}) \quad A-1$$

-- *Step 3: Calculate the fuzzy weights.* The fuzzy weight \tilde{w}_i of indicator i is:

$$\tilde{w}_i = (l_i, m_i, h_i) = ((\prod_{j=1}^n l_{ij})^{\frac{1}{n}}, (\prod_{j=1}^n m_{ij})^{\frac{1}{n}}, (\prod_{j=1}^n h_{ij})^{\frac{1}{n}}) \quad A-2$$

-- *Step 4: Obtain the crisp weights.* The crisp weight w_i of the indicator i is:

$$F(\tilde{w}_i) = (l_i + 2m_i + h_i) / 4$$

$$w_i = F(\tilde{w}_i) / \sum_{j=1}^n F(\tilde{w}_j) \quad A-3$$

B. The calculation steps for supplier flexibility

-- Step 1: Establish the $m \times n$ decision matrix $T = [x_{ij}]$ with m suppliers and n flexibility indicators. For a quantitative indicator, x_{ij} is the numeric value of the performance of supplier i against indicator j . For a qualitative indicator, x_{ij} is a TFN representing the judgement of the decision makers.

-- Step 2: Normalise the decision matrix by linear normalisation.

--Step 3: Construct the weighted normalised decision matrix $V = [v_{ij}]$. The weights of the indicators are accommodated to the normalized decision matrix. Let w_j be the weight of indicator j , the matrix V is:

$$\tilde{v}_{ij} = w_j \times x_{ij} \quad \text{A-4}$$

--Step 4: Determine the best flexibility solution A^* and worst flexibility solution A^- . A^* contains the largest judgement value of each column of matrix V , and the largest/smallest numeric value of each column if it is a benefit/cost indicator (against which numeric values are used). A^- contains the opposite.

$$\begin{aligned} A^* &= \{v_j^* \mid \max_i v_{ij} \text{ if } j \in J_1, \min_i v_{ij} \text{ if } j \in J_2, i = 1, 2, \dots, m\} \\ A^- &= \{v_j^- \mid \min_i v_{ij} \text{ if } j \in J_1, \max_i v_{ij} \text{ if } j \in J_2, i = 1, 2, \dots, m\} \\ J_1 &: \text{indicator taking subjective judgment or benefit indicator taking numeric value} \\ J_2 &: \text{cost indicator taking numeric value} \end{aligned} \quad \text{A-5}$$

--Step 5: Calculate the distances of each supplier to A^* and A^- , denoted as F^+ and F^- respectively.

$$\begin{aligned} F_i^+ &= \sqrt{\sum_{j=1}^n (v_{ij} - v_j^*)^2} \\ F_i^- &= \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \end{aligned} \quad \text{A-6}$$

--Step 6: Calculate the flexibility value of each supplier by comparing F^- with total distance (i.e. $F^+ + F^-$). The most flexible supplier is the one who gets the maximum value.

$$\text{Flexiblity of supplier } i = F_i^- / (F_i^+ + F_i^-) \quad \text{A-7}$$

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